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Quantum Computing: Evolution or Revolution?

STATE STREET GLOBAL ADVISORS

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Quantum Computing: Evolution or Revolution?

As analysts and portfolio managers, we possess an innate curiosity for emerging technologies, recognizing their potential to both create opportunities and disrupt industries within our investment portfolios. The rapid ascent of Generative AI stands as a testament to this transformative power. As we navigate this dynamic landscape, our attention is drawn towards another prospective game-changer encompassing academia, public companies, private companies, and even nation states: Quantum Computing. We are not physicists and we do not claim to be quantum computing experts — our endeavor has been to understand what quantum computing is, its current state of development and its potential significance for the industries and companies we invest in on behalf of our clients. This paper chronicles our exploration and investment insights into this cutting-edge field.

What is Quantum Computing?

Quantum computing, an innovation most find difficult to define and understand, might be the next great advancement in modern computing. Quantum computing applies the laws of quantum mechanics to simulate and solve complex problems that are too computationally difficult for the current state of classical computers.[1]

Even as classical computers continue to improve in speed and power, there are certain problems that computer scientists do not expect them to ever be able to solve. Quantum physics gives quantum computers computational abilities beyond those of classical computers, enabling certain problems to be solved exponentially faster than classical computers.[2] Examples include simulating the behavior of matter, analyzing compounds to create new drugs, optimizing factory floors or global supply chains, and identifying fraud and risk patterns in financial transactions, among others.[3]

The Source of Quantum Computing Power

The source of quantum computing power comes down to the interplay of *superposition, interference and entanglement*.[4] In classical computing, information is stored in bits, which can take the value of either 0 or 1. Quantum computers instead use quantum bits, or qubits, which are subatomic particles that extend beyond just 0 or 1 — they can be in a *superposition*, or a complex combination of both 0 and 1. These complex combinations enable an exponentially large amount of possible solutions to a problem.[5] The more qubits, the greater potential for solving difficult problems.[6]

Interference involves manipulating qubits so their states combine *constructively* during computations to amplify correct solutions and *destructively* to suppress the wrong answers. Constructive interference is when the peaks of two waves — like sound or water waves — combine to create a higher peak. Destructive interference is when a wave peak and a wave trough combine and cancel each other out. Quantum algorithms, currently few and difficult to devise, set up a sequence of interference patterns that yield the correct answer to suitable problems.[4]

Entanglement establishes a uniquely quantum correlation between qubits: The state of one cannot be described independently of the others, no matter how far apart, and entanglement's collective behavior enables computational speed-ups beyond the reach of classical computers.[4] For qubits to be useful, however, it is also important they maintain coherence — the ability of quantum systems to maintain a stable phase relationship between different quantum states over time.[7]

Beyond the theory, scientists are also striving to achieve *quantum advantage*, or the ability to solve problems beyond the reach of classical computers. Even more relevant for investors will be the achievement of *quantum economic advantage* — when a particular problem can be solved more quickly with a quantum computer than with a *comparably priced* classical computer.[8]

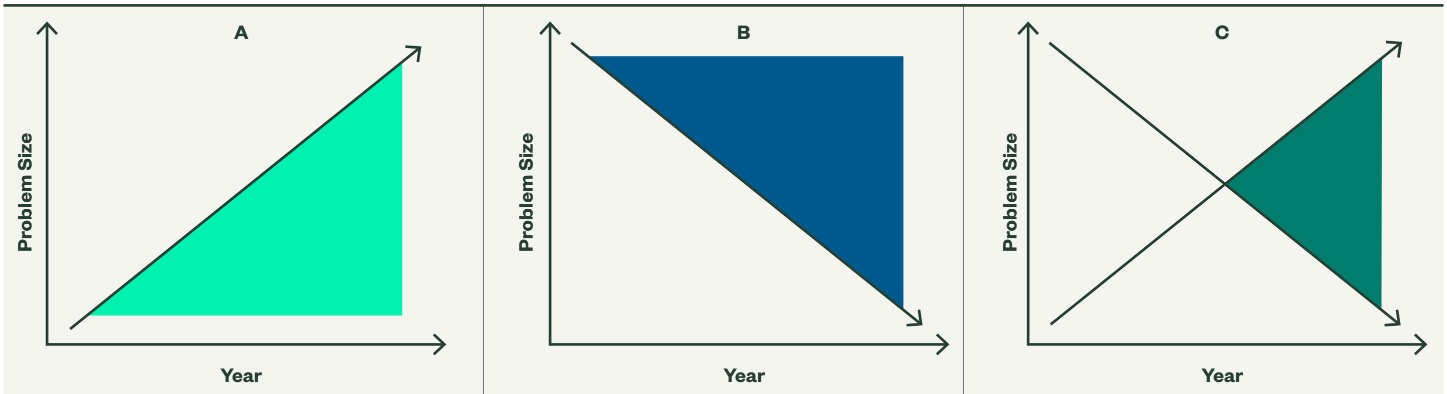
To determine quantum economic advantage, business and technology leaders need to consider two conditions:

- **Feasibility** whether a quantum computer exists that is sufficiently powerful to solve a particular problem

- **Algorithmic Advantage** when a quantum computer is faster at completing a particular task than a comparably priced classical computer[9]

As discussed in an MIT research paper and depicted graphically below, the overlap between the two is *quantum economic advantage*. Neil Thompson, a research scientist at MIT's Computer Science and AI Lab, also advises businesses to consider the speed of the computer versus just the algorithms; unless the improvement is an economical one, simply deploying classical computing may suffice.

When Quantum Economic Advantage Will Occur



Feasibility	Algorithmic Advantage	Quantum Economic Advantage
Quantum computers are powerful enough to solve a particular problem size.	When a better quantum algorithm provides enough advantage to overcome the speed advantage of equally expensive classical computers.	(overlapped regions of A + B) = Quantum computers are faster + Quantum computers can solve

Credit: "The Quantum Tortoise and the Classical Hare: A Simple Framework for Understanding Which Problems Quantum Computing Will Accelerate (and Which it Won't)." Sukwoong Choi, William S. Moses, and Neil Thompson.

How is Quantum Computing Different from Classical Computing?

Quantum computing is imposing due to its abstract and counterintuitive nature. However, at its core the mathematics simply extend classic laws of computation to the peculiarities of quantum mechanics.

Classical computing performs calculations with simple on-off switches and a binary process where each basic unit of information is stored as a 0 or 1, processed through logic gates in a single-thread and remain definite and observable.[10] Quantum computing, however, allows each switch to be both on and off simultaneously, and even linked with the state of other switches regardless of the distance between them. Thus, qubits exhibit behaviors associated with probabilities rather than certainties, allowing quantum computers to process a tremendous number of possibilities simultaneously, making them potentially far more powerful than classical computers for certain tasks.

As described above, quantum computers use qubits capable of being in any state of 0, 1, or any quantum superposition in between. Importantly, superposition does not just refer to switching quickly between states, but rather being in a blend of states, much the same way as musical notes played together form a chord. When a qubit is in superposition, it holds a combination of all possible binary states (e.g., both 0 and 1), and only when measured does it collapse to one definite state. This multitude of states enables quantum computers to process a multitude of potential outcomes simultaneously, vastly increasing their computational ability for certain types of problems.[11]

The Concept of 'Spin'

In quantum physics, each particle has a characteristic known as "spin", a unique behavior unlike anything we see in our everyday world. It isn't actually spinning, but this concept helps us predict how particles will act in magnetic fields and how they will interact with each other.

To illustrate the concept of spin, imagine you have a pair of dice that, instead of numbers, show either an up arrow or down arrow. In the quantum world, each die doesn't calibrate on up or down until one looks at it. Before one looks at it, each die is in a strange state of being both up and down at the same time. Also, unique to quantum mechanics is the special situation called the "singlet state" for these two dice. When they are in this state if you look at your die and see an up arrow, then, no matter how far away your friend is, say as far away as Australia, when they look at their die they will see a down arrow, and vice versa. And the moment you look at your die, the state of your friend's die is instantly determined.[12]

This link or connection between the two dice, introduced earlier as entanglement, is what makes quantum mechanics so unique and captivating — almost as if the two dice are communicating instantly across vast distances, faster than the speed of light and contrary to conventional theory of information travel. This property highlights the strange but fascinating world of quantum mechanics, where objects just don't behave the way things do in the regular world.

The Power of Qubits

How quantum computers perform calculations also helps to explain how they differ from classical computers. A classical computer's power increases linearly with the addition of more bits. More bits mean more binary information, which increases the computational capacity but does not exponentially change the processing speed or capability. The power of a quantum computer, however, increases exponentially with the addition of more qubits. Scientists at Google first tested the company's Sycamore quantum computer using cross entropy benchmarking (XEB) in 2019, demonstrating that it could complete a calculation in 200 seconds that would have taken the world's most powerful supercomputer at the time 10,000 years to finish. They registered an XEB result of approximately 0.002 with the 53 superconducting qubits built into Sycamore.[13]

With this basic understanding of the key differences between classical computing and quantum computing, we highlight some of the different quantum technology approaches being deployed.

Quantum computing can be characterized by various underlying approaches being deployed to the specific technologies governing their inner workings. We cover five key approaches here:

1 **Superconducting** qubits leverage the properties of superconducting materials to conduct electricity without resistance when cooled to very low temperatures. Superconducting qubits exploit this feature to create states that can exist in superposition *and* entanglement. These qubits are typically created using tiny circuits made from superconducting materials that allow currents and magnetic fields to flow in such a way that their quantum states can easily be manipulated and read. This technology allows for precise control and scalability and thus is critical for the advancement of practical quantum computing applications. In addition superconducting qubits are preferred for their relatively easier integration with existing semiconductor technologies and have been extensively developed by companies like **IBM** and **Google**.[14]

2 **Trapped Ion** qubits involve trapping ions (charged atoms) using electromagnetic fields and lasers to manipulate their quantum states. This technology is known for high fidelity and long coherence times, making it ideal for precise quantum operations. Companies such as **IonQ** and **Quantinuum** are the leading players in this domain.[15]

3 **Photonic** qubits use photons, particles of light, to carry quantum information. Unlike other quantum computing technology approaches, photonic quantum computing does not require cooling to near absolute zero, and potentially can operate at room temperature. This is a major advantage over other approaches, making photonic qubits naturally suited for integration into existing fiber optic-based communication networks. However, photons are challenging to store and manipulate, which makes it difficult to implement quantum gates and error correction schemes.[16] Companies such as **Xanadu** and **PsiQuantum** are exploring this approach.

4 **Topological** qubits, proposed by **Microsoft**, are based on exotic quasiparticles called anyons which, due to their unique nature, theoretically provide built-in error correction. While still in the experimental stage topological qubits promise to reduce the need for error correction significantly.[17]

5 **Silicon Spin** qubits are the most similar to traditional CPUs and use the spin of electrons or nuclei in silicon to encode quantum information. This approach could potentially leverage existing semiconductor manufacturing technologies, making it attractive for scalability. Perhaps unsurprisingly, **Intel** as a major semiconductor manufacturer, is focused on this approach.[18]

The Potential Benefits and Risks of Quantum Computing

According to McKinsey, quantum computers have four fundamental capabilities that differentiate them from classical computers: 1) *quantum simulation* in modeling molecules; 2) *optimization and search* by dramatically narrowing the range of possible answers; 3) *quantum AI* working with better algorithms to transform and dramatically speed up training and use of machine learning; and 4) *prime factorization*, in calculating complex prime numbers for encryption.[19]

Potential Benefits

It is important to highlight research efforts in quantum physics, mechanics and theory have been ongoing for longer than quantum computing itself and will likely lead to further breakthroughs to accelerate development of quantum computing. The combination of a better understanding of quantum systems by physicists, the exponentially faster speed of quantum computing and development of software to better leverage these two is likely to result in quantum computing having a significant impact across different sectors of the economy.

- The tremendous speed of quantum computing can be leveraged to solve complex and analytical problems like simulation. Simulation in quantum systems can revolutionize not only understanding of how molecules behave but also understanding how the universe works as some researchers believe quantum mechanics applies to objects both small and large.[20]

- The pharmaceutical industry can benefit from quantum computing and quantum mechanics as drug molecules are quantum systems themselves, more suitably simulated by quantum computers than classical computers, and can result in higher success rates for new drugs.[21] Similarly, the manufacturing and industrial sectors will benefit from quantum computing as they typically invest resources in the development of new materials at the molecular level.

- Industries that invest heavily in the development of computer hardware, like the semiconductor industry, and those that spend heavily in the consumption of computer speed and power, like the software industry, should see accelerated levels of innovation not possible under classical computing.

- Within the technology sector, companies focused on high performance computing and specifically machine learning and AI can leverage the superior speed and algorithms associated with quantum computing. Because of quantum computing's fundamental differences to classical computing, algorithms written to leverage those differences, particularly in machine learning and AI, are much more complex and can achieve much faster results. To prove the point, a collaboration by Caltech, Harvard, Berkeley, Microsoft and Google showed that quantum machine learning algorithms can learn more quickly than a classical machine learning algorithm.[22]

The Travelling Salesperson Example

To understand the incredible potential for quantum computing to solve difficult and even currently unsolvable problems, it is helpful to look at the well-known travelling salesperson computer science problem, which asks for the shortest route for a salesperson to visit 30 cities. This seemingly simple problem actually has so many variables it would take 20+ trillion years (for reference our universe is about 14 billion years old) to solve using classical computers. Quantum computers, however, given their exponential ability for parallel simultaneous calculations can potentially solve this optimization problem in hours or days. The positive implications for the logistics industry are obvious and substantial, saving tremendous amounts of costs and time.[23] Beyond logistics, according to McKinsey, the potential increase in economic value from just quantum computing alone, could reach nearly $1.3 trillion by 2035.[24]

Lastly, quantum computing has the potential to drive major breakthroughs needed to help solve the climate crisis. According to an interview by McKinsey with Jeremy O'Brien, CEO and cofounder of **PsiQuantum**, a quantum startup dedicated in part to sustainability use cases, quantum computing will revolutionize chemistry. In doing so, quantum computing breakthroughs can lead to higher density batteries, more efficient solar panels, point source carbon capture, zero-carbon cement, cost-effective hydrogen and green ammonia fuels.[25] Additionally, from an environmental point of view, while a supercomputer uses enough energy to power 50,000 homes, a quantum computer requires only 30–40kWs and, therefore, can be up to 40x more energy efficient than classical computers.[26]

Potential Risks

Quantum computing may have many positive societal and economic benefits, but as with every technological breakthrough there will be downsides and risks to consider as well. To begin with, the significance of these benefits and risks has resulted in quantum technologies becoming a matter of national security for many countries including the US and China, compelling them to invest tens of billions of dollars in quantum computing research and development.[27]

And while there are some benefits and risks associated with quantum computing that will be easily identifiable, others will be unforeseen, much like how eye surgery was not contemplated as a potential application of laser technology when it emerged in the 1960's.

The risks of quantum computing derive, in part, from the disruptive impact of the technology itself, in much the same way the internet structurally disrupted print media, but can also come from the use of the technology in the hands of bad actors.

In an ironic twist, quantum computing could drive such a significant improvement in productivity it could drastically reduce employment levels. Similarly, it could significantly benefit smaller segments of the population, thereby exacerbating the digital divide as the significant costs associated with quantum computing could mean that only wealthy nations, companies or people will be able to afford it.

Examples of risks from quantum computers being used by bad actors include rendering modern encryption methods useless and breaking into government or corporate databases. Quantum computing applied to AI and machine learning could also be used to generate deep fakes and false information to manipulate people or perform illegal activities difficult to identify by traditional security techniques.[28]

It will be incumbent upon the entire quantum ecosystem as well as governments to research, prepare and account for the risks associated with quantum computing as much as possible *before* expected breakthroughs lead to practical adoption.

Assessing the Risk of Quantum Computing to Encryption and Security

Quantum Computing, as it stands today, does not yet represent a significant risk to existing encryption and security solutions. However, future quantum computers will almost certainly be able to quickly break our current encryption protocols.

Even with the advanced state of cryptography protocols today, it would take a classical computer trillions of years to break existing encryption protocols. Based on Moore's Law, as classical computers become more powerful, it should take less time for them to break an encryption algorithm. However, even if compute power continues to double every 18 months and the amount of time to crack an algorithm reduces by 100 times every 10 years, current encryption algorithms would still not be able to be cracked by a classical computer in our lifetimes.

The story is very different for quantum computing. Experts believe we are only about 10–20 years from achieving a quantum computer powerful enough to break our current encryption algorithms in just hours. This is a concern, not just because we need to migrate to more robust encryption policies before this happens, but also because encrypted data sent today could be stored by bad actors and broken in the future with a quantum computer. Thus information or data that needs to be kept secret for more than 20 years might already be vulnerable today.

To account for this, government agencies (such as the National Institute of Standards and Technology or NIST) are working to implement more robust encryption protocols that can be widely implemented on today's classical computers, yet would still require an unreasonably large amount of time for quantum computers to break. As progress is made with quantum computers, it is only a matter of time before these more robust algorithms are needed and, even so, for some secrets it may already be too late.[29]

How Far Away is Quantum Computing From Practical Use?

Quantum computing still has a long road ahead before it becomes mainstream technology, and it faces several significant obstacles before achieving widespread practical use.

The main obstacles to quantum computing include:

- **Qubit Stability/Decoherence** The delicate nature of quantum systems makes them extremely vulnerable to the slightest disturbance, whether a stray photon created by heat, a random signal from the surrounding electronics, or a physical vibration. This noise wreaks havoc, generating errors or even stopping a quantum computation in its tracks.[30]

- **Error Correction** Errors in today's quantum computers limit current applications mainly to exploration and discovery. A dramatic reduction in error rates will be required for quantum computing to be commercially viable.[31] Today, a great deal of the work in the field of quantum computing is devoted to realizing error correction — a technique enabling noise-free quantum computation on very large quantum computers.[32]

- **Scalability** Achieving quantum computing's potential hinges on the ability to build larger and more powerful quantum computers, however, efficiently integrating and controlling growing numbers of qubits remains a significant challenge.[33]

- **Cryogenic Requirements** Quantum systems often operate at temperatures close to absolute zero (0 Kelvin or -273.15°C), demanding sophisticated cooling techniques to eliminate thermal noise and enhance quantum coherence.[34] As quantum computers become larger, the size and power requirements of the cooling equipment become increasingly more expensive, both from a cost and environmental standpoint.[35]

- **Complex Hardware Development** It's not just all about scaling the number of qubits. Hardware innovations in gate operations and quantum networking will also be required for quantum computers to operate reliably at scale.[36] As an example, IBM added gate operations as a new metric on their 2033 quantum roadmap.

- **Standardization** Currently the market is highly fragmented and lacks standards across programming, middleware and ecosystems, thus exposing companies investing in such a range of potential platforms to innovation risk.[37]

Other challenges to quantum computing achieving practical use include: limited availability of quantum software, the need to integrate with classical computers, and a limited pool of talent with the necessary skills.[38]

In a recent interview with the Wall Street Journal, the IBM team indicated they expect quantum computing to enter mainstream industries in the next 6–10 years.[39] This timeline could prove to be optimistic, however, with a recent McKinsey article suggesting that many within the quantum community remain skeptical. Based on conversations with technology executives, investors and academics in the quantum computing field, McKinsey reports that 28% believe we won't see a fully fault tolerant quantum computer until 2040 or later.[40]

Although mainstream practical use still appears many years away, some companies are already demonstrating quantum computing can deliver real business value. The following examples are quoted in a May 2023 article by BCG Consulting:

"IBM has improved machine learning for fraud detection, reducing false negatives by 5%, compared with the results from a classical-only model. QC Ware and Goldman Sachs have outperformed classical computers on Monte Carlo simulations, a widely-used technique in option pricing and risk management. [And] Crédit Agricole has teamed up with Pasqal and Multiverse Computing to predict deteriorating credit scores with the same level of precision and recall as the bank's classical random forest model with 96% fewer initial classifiers."[41]

These results were achieved in laboratory circumstances, but point clearly toward real business usage. Assuming quantum computing hardware companies continue to deliver on technology-development roadmaps (which has been the case for the past several years) and software continues to make better use of the hardware, BCG believes these milestones point to enterprise-grade quantum computing generating business value by 2025.[42]

Recent reports from technology research and consulting firm Gartner also indicate early adopters may derive near-term benefits from investments in quantum computing, even though the technology is expected to take at least a decade to reach full maturity. Gartner predicts by 2027, 25% of large enterprises will deliver an evolutionary advantage over (non-quantum-enabled) peers through quantum-inspired initiatives.[43]

The Major Players in Developing Quantum Computing

Some of the world's leading technology companies are at the forefront of developing quantum computers, while a number of startups are also emerging as important players.

IBM Quantum Computing

> **"We are living in the most exciting time in the world of computing, probably since the advent of either the digital computers in the 1940s or the transistor in the late fifties"**
>
> — Dario Gil (Director of IBM Research), IBM Quantum Summit December 2023

IBM has been a pioneer in quantum computing, working on the technology since the early theoretical founding of the industry. IBM's quantum computing journey began in 1970, when IBM research fellow Charles H. Bennet coined the term 'quantum information'.[44] Research efforts gained momentum in the 2010s, culminating with the launch of the first quantum system in the cloud in 2016.[45] Since then IBM has made significant advancements in developing its quantum architecture, systems, hardware and a framework to make the technology usable and accessible.[46] IBM's Quantum Network of partners, which was launched in 2017, has more than 270 members, including leading Fortune 500 companies, internationally recognized universities and laboratories and cutting edge start-ups.[47] IBM Quantum is part of IBM's Research group and employs several hundred people with teams dedicated to hardware, software development, cloud services, consulting services and applications.[48] Key milestones achieved prior to 2023 include:[49]

- **2016** IBM introduces Quantum computing as a cloud service
- **2017** Release of Qiskit, IBM's open-source software development kit for quantum computing
- **2018** IBM's first Quantum Innovation Centers opened
- **2019** Launch of IBM Quantum System One
- **2021** IBM's Eagle processor broke the 100 Qubit barrier

2023 was a significant year for IBM Quantum. In December of that year, IBM hosted a Quantum Computing summit heralding the dawn of a new era in quantum technology dubbed 'the era of Quantum Utility'. This concept underscores the transformative potential of large scale quantum systems of over 100 qubits to solve problems that classical computers cannot, thereby creating 'business advantage'.[50] This summit followed IBM's groundbreaking announcement in June 2023, when the company showcased the attainment of 'Quantum Utility' in an experiment corroborated by scientists at UC Berkeley and featured prominently on the cover of the prestigious scientific journal Nature. The experiment marked a historic first, demonstrating the capacity of quantum computers to deliver precise outcomes at a scale surpassing conventional classical approaches.[51]

Further developments unveiled at IBM's Quantum Computing Summit include:[52]

- A new 133 qubit processor called Heron, which claims to be the most advanced quantum processor in the world.
- A new quantum system called IBM Quantum System Two, featuring a new modular computing architecture for future scaling.
- An extended roadmap (to 2033), which aims to achieve error-corrected quantum computing by 2029, addressing one of the most significant issues with today's systems.

IBM's ultimate goal is to build 'quantum-centric supercomputers', which will incorporate both quantum and classical processors and communication networks, all working together to transform how we compute.[53] IBM's technological approach is based on superconducting qubits ('metal on a substrate'), which competes well on scale, quality and speed versus alternative approaches:[54]

IBM is widely recognized as a leader in the quantum computing industry. External validation includes IBM's position as the sole market leader in the IDC MarketScape: Worldwide Quantum Computing Systems Vendor Assessment, published in September 2023.[55]

Google Quantum Computing

In 2006, Google started exploring how quantum computing might help efforts to accelerate machine learning, which led to the founding of the Google AI Quantum team. In 2014, John Martinis, one of the world's foremost experts in quantum computing and his team at the University of California at Santa Barbara joined Google in their efforts to build a quantum computer.[56] The company built a Quantum AI campus in Santa Barbara, CA which includes their quantum data center, fabrication facility, and cutting-edge research.[57]

Google is focused on a 'full stack approach' to quantum computing, the seamless integration of hardware and software components — from quantum processors, control and decoding hardware and cryostats to the operating system and user facing software. Google believes this integrated methodology supports the acceleration of advancements in both the capabilities of quantum systems and the potential applications they can power.[58] In 2019, Google demonstrated quantum computing is a practical reality, instead of just a theoretical one. Physical qubits lasted long enough to do some specific calculations faster than the world's most powerful classical supercomputer, introducing the Noisy Intermediate Scale Quantum (NISQ) computing era. NISQ computers can perform tasks with imperfect reliability, but beyond the capability of classical computers. Even with imperfect reliability, knowledge of science can advance in the NISQ era.[59] In 2023, the team was the world's first to report scalable quantum error correction with an experimental demonstration of error reduction by increasing the number of qubits. Both of these milestones are critical to achieving a large-scale error-corrected quantum computer.[60]

Google's mission is to build best-in-class quantum computing for otherwise impossible problems.[61] In March 2024, Google Quantum AI and Google.org announced that they have joined XPRIZE and the Geneva Science and Diplomacy Anticipator (GESDA) to launch XPRIZE Quantum Applications, a three-year, $5 million global competition to apply quantum computing to solve real-world challenges. The competition aims to generate quantum computing algorithms that can be put into practice (today or in the future) to help achieve societally beneficial goals, like those described by the United Nations Sustainable Development Goals (SDGs).[62]

In their announcement of the competition, Google noted —

> "*... most quantum algorithms have been studied primarily in the context of abstract mathematical problems. Less work has gone into assessing those algorithms for specific, real-world use cases. Likewise, much less effort has gone into quantifying how large a quantum computer is needed for a decisive quantum advantage over classical computing in such problems.* ***While there are many reasons to be optimistic about the potential of quantum computing, we're still somewhat in the dark about the full scope of how, when, and for which real-world problems this technology will prove most transformative.*** *We hope launching this prize will help to shed light on these questions — by incentivizing the community to advance and more thoroughly anticipate the positive impact of quantum computing on society.*[63]

Microsoft Quantum Computing

Like Google, Microsoft has been working on Quantum Computing technology since 2006.[64] The company is spreading its bets, however, by partnering with other companies, including Quantinuum, where the two companies had a breakthrough in making quantum computers more reliable. Recently, Quantinuum and Microsoft achieved 14,000 separate quantum calculations without an error.

Microsoft has taken a unique approach to quantum computing attempting to build a quantum computer with topological qubits, based on a phase of matter, making them more stable. While more challenging in the near term, Microsoft hopes topological qubits will make it easier to create commercial quantum computers in the future.

Similar to Google, Microsoft is looking to build a complete stack, moving from the quantum computer to the software running on top. As part of this, Microsoft has created its own coding language, Q#, for coding on top of quantum computers. Q# is similar to C#, but is adapted specifically for the way that quantum computers operate.

While Microsoft does not have a commercially viable quantum computer currently, its goal is to create an industrial scale quantum machine with more than one million qubits and to provide a cloud quantum solution via its Azure Cloud platform.[65]

Intel Quantum Computing

Intel began researching quantum computing in the early 2010s and given its long history as the dominant player in classical x86 CPU computing, Intel also has major ambitions to develop and provide the entire quantum computing hardware and software stack, as well as serve as a major quantum computing foundry for production of atom-based silicon spin Quantum Processing Units (QPU). As practical and commercial applications of quantum computing remain years if not decades away, all of Intel's quantum efforts are concentrated in its research arm, Intel Labs.

Intel Labs is actively working to achieve quantum practicality, the transition of quantum technology from the lab to commercial quantum systems solving real-world problems. Today's quantum systems include only tens or hundreds of entangled qubits, limiting them from solving real-world problems. To achieve quantum practicality, commercial quantum systems need to scale to thousands or even millions of qubits and overcome challenges like qubit fragility and software programmability. Intel Labs is working to overcome these challenges with the help of industry and academic partners and has made significant progress.

First, Intel is leveraging its expertise in high-volume transistor manufacturing to develop 'hot' silicon spin-qubits, much smaller computing devices that operate at higher temperatures. Intel recently released its most advanced quantum chip named Tunnel Falls. This chip has silicon spin qubits up to 1 million times smaller than other qubit types.[66]

Second, Intel's second generation Horse Ridge II cryogenic quantum control chip provides tighter integration, by bringing key control functions for quantum computing operation into the cyrogenic refrigerator — as close as possible to the qubits themselves — to streamline complexity of control wiring for quantum systems.[67]

And third, Intel's cryonic refrigerator, the Cryoprober, enables high-volume testing that is helping to accelerate commercialization. Cryoprober can plunge a 300-millimeter silicon wafer to the extraordinarily low temperature of 1.7 kelvins — just a hair above absolute zero.[68]

Even though it may be years away from large-scale implementation, Intel remains committed to quantum research as it believes it will deliver breakthroughs in materials, chemicals and drug design, financial and climate modeling, and cryptography.[69]

Amazon Quantum Computing

The quantum computing footprint of Amazon Web Services (AWS) includes basic research, hardware design and providing customers with access to quantum computing through AWS. In 2019, the company established the AWS Center for quantum computing at CalTech which houses quantum theorists, software designers and hardware engineers.[70] The company also established the AWS Center for Quantum Networking.[71]

AWS customers may access quantum computing as a managed service through Amazon Bracket. Through Bracket, customers use quantum computers provided by quantum startups like IonQ, OQC, Rigetti and QuEra.

The company also created Amazon Quantum Solutions Lab which allows customers access to quantum computing experts. These experts can help users identify quantum use cases in their businesses and build and test algorithms on Bracket.[72]

Nvidia Quantum Computing

Realizing the potential for graphic processing units (GPU) to simulate perfect qubit calculations (i.e. a qubit performing without errors), Nvidia began investing in quantum computing in 2019, and as the dominant provider of GPU-accelerated computing and processors used to train AI and Gen AI large language models (LLMs), Nvidia has become increasingly critical in enabling the development of quantum computing. In conjunction with classical computing and AI, quantum computing will impact applications across the many industries that can benefit most from the potential of its tremendous compute capability.

To prepare for future deployment of quantum computing, governments, universities, and industries are investing in hardware, software, and algorithm development. NVIDIA's internal division Nvidia Quantum leverages its hardware and software platforms to enable the entire quantum ecosystem and assist them in researching, developing and building their own quantum computing networks.[73]

True to its philosophy of investing heavily only in its core competency, namely GPUs, and leveraging that technology across multiple applications (e.g., Gaming, AI) to maximize its return on investment, Nvidia has no intentions to ever develop its own QPU, and is open to partnering and working with any and all qubit technology approaches. Instead, Nvidia believes its best opportunity to advance the field of quantum computing is to offer custom quantum solutions to the Quantum Ecosystem.[74] This Ecosystem includes:

- Quantum Hardware Builders
- Quantum Simulation Networks
- Systems Builders and Integrators
- Quantum Software and Systems
- Research Centers
- Cloud Service Providers

Startups in Quantum Computing

Quantum Computing is already a crowded market with more than 600 start-ups.[75] Beyond the established technology giants, we did some high-level research into a number of the high-profile start-ups in the space. Notably, the valuations of the publicly listed quantum computing companies have collapsed from 2021/2022 levels, reflecting the difficulty of operating in the public market with such a nascent technology and business, particularly in a higher interest rate environment.[76] Our findings are summarized in the following table:

Company	Technology Approach	Latest Valuation	Ownership	Background	Notable Partnerships
Quantinuum	Trapped Ion	$5.0bn (2024, $625m funding to date)	Private — Honeywell is majority shareholder	Formed through a merger of Cambridge Quantum computing and Honeywell Quantum Solutions in November 2021	Microsoft
IonQ	Trapped Ion	$1.6bn (peak was $6bn in November 2021	Public (US-listed), IPO in October 2021	Founded in 2015 after 25 years of academic research; affiliated with University of Maryland and Duke University. Team of 300+ employees and $6m revenue	Cloud partnerships with Amazon, Microsoft, and google
Xanadu	Photonic	$1bn (2022, $275m funding to date)	Private (Canada)	Founded in 2016 in Toronto. Team of 170+ people. Developed open-source quantum software library Pennylane	Amazon, IBM, Google, Nvidia, other quantum start-ups
Infleqtion/ ColdQuanta	Cold Atoms	Est. $0.5–1bn	Private	Founded in 2007, also known as ColdQuanta. Team had 90+ PhDs	NASA
Rigetti Computing	Superconducting Gate	$174m (peak was >$1bn in March 2022)	Public (US-listed), IPO in March 2021	Founded in 2013 in California. Founder came from IBM Quantum	Amazon, Microsoft
D-Wave	Both Quantum annealing and Superconducting Gate	$156m (peak $1bn in August 2022)	Public (US-listed) since August 2022	Founded in 1999 in Canada. Team of 180+ with 40 PhDs	Blue chip customers including: IPG, Accenture, J&J, Mastercard

Source: State Street Global Advisors research using company websites, Bloomberg, Gartner's February 2024 Quantum Computing briefing and referenced media articles.[76] Listed company valuations are as of August 27, 2024.

Investment Implications of Quantum Computing

Our goal in writing this paper was to better understand what quantum computing is, its current state of development, and its potential significance for the industries and companies we invest in on behalf of our clients. Because of the physics behind quantum computing, it is *fundamentally different* than classical computing and, therefore, possesses unique and substantial advantages in processing complex problems and speed. These advantages will result in profound disruption to the status quo of certain tasks and industries.

Over the past three decades, tremendous progress has been made in quantum research and development; in some cases very transparent progress, but in other cases less so. In the scientific and academic communities, as with most technology development, progress in quantum computing is by and large transparent and shared openly to advance the field. With most public companies where we focus our investment efforts, their progress and even roadmaps are also shared as part of their public disclosures. And disclosed progress has indeed been significant, to the point where some of quantum computing's leaders are achieving early quantum advantage milestones. Companies in the private sector, however, are by definition less transparent, and certainly most nation states' development of quantum computing is not transparent at all for obvious national security reasons. The fact that breakthroughs, which may happen behind the scenes, could lead to significant relative economic and or military advantage sooner than expected makes understanding and monitoring quantum computing even more important for investors. The results of our team's research have led us to the conclusion that while quantum economic advantage may be years if not decades away, for a select number of applications, quantum computing may achieve relative quantum utility much sooner.

While quantum computing remains an emerging field with considerable uncertainty in the near term, our research leads us to believe potential winners are likely to be the major tech companies that have been investing in quantum computing for years, steadily advancing the technology. Their financial muscle allows them to sustain long-term research efforts. Their strong brand recognition helps attract top-tier talent, a critical factor given the specialized skills required. This combination of deep pockets, strategic patience and access to talent, positions them well to potentially lead in the quantum computing race. And as for potential losers, we believe companies not actively exploring the technology and its potential to understand its impact to either benefit or disrupt their status quo are most likely to get blindsided — we have seen this play out to a certain extent in the adoption of AI.

We view some companies as having attractive upside optionality from quantum computing, but as long as it remains in the R&D phase with no clear dominant technology or platform yet established, we find it difficult to base an investment case on the technology either way. And given even the leading quantum players are still at the point of pursuing different foundational qubit technology approaches, and face various challenges to achieving quantum scale, quality, and speed, it is clear from our research that achieving practical quantum economic advantage is likely to be at least a decade away (e.g. IBM's 2033 roadmap), if not longer.

Our research also led us to conclude quantum computing will not replace classical computing and, in fact, is almost always integrated with classical computing in order to process the results of quantum calculations. This is an important, and often misunderstood point, and is the reason why all current leaders in classical computing are also leading the development of quantum computing as both a defensive and offensive move.

If nothing else, the stunning and rapid pace of breakthroughs in AI and Gen AI's advancement in just one year have taught us breakthroughs in quantum computing may happen much sooner than we think. Armed with the knowledge and insights we have gained from our research on this topic, we will monitor the progress of quantum computing closely to assess who might become potential winners and losers, as much as possible in advance of these breakthroughs, to best position our clients' portfolios to take advantage of opportunities and hedge against risks as quantum computing breakthroughs occur.

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* Pensions & Investments Research Center, as of December 31, 2023.
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